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Mechanical Properties and Organic Carbon of Soil Aggregates in the Northern Appalachians

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ABSTRACT

Aggregate properties determine the macroscale structural condition of the soil. Understanding of impacts of no-till and traditional agricultural practices on the mechanical properties of aggregates is fundamental to soil management. This study assessed the tensile strength (TS), bulk density (ρ_{agg}), soil moisture retention (SMR), and soil organic C (SOC) concentration of soil aggregates and determined the interrelationships among aggregate properties under long-term moldboard plow (MP), chisel plow (CP), disk with beef cattle manure (DM), no-till with beef cattle manure (NTM), no-till without beef cattle manure (NT), pasture, and forest systems in the North Appalachian region. Properties were determined on 1- to 8-mm aggregates from 0- to 30-cm soil depth. The TS and SMR (0 to −333 kPa) in NTM were higher than those in MP and CP ($P < 0.01$). The SOC concentration for NTM was higher than that for MP, CP, and NT ($P < 0.01$). The ρ_{agg} was 1.35 Mg m^{-3} in NTM and approximately 1.61 Mg m^{-3} in MP and CP ($P < 0.01$). Manuring had a positive and excessive tillage negative impact on aggregate properties. Aggregates from forest had the lowest TS (63 kPa) and ρ_{agg} (0.99 Mg m^{-3}) and the highest SOC concentration (70 g kg^{-1}), whereas the MP and CP had the highest TS (approximately 358 kPa) and the lowest SOC concentration (14 g kg^{-1}) in 0- to 10-cm depth ($P < 0.01$). Mean ρ_{agg} was significantly higher than the density of bulk soil (ρ_b). The log-transformed TS (LogTS) increased with increasing ρ_{agg} and decreased with increasing aggregate size and SOC. Size, SOC concentration, and ρ_{agg} explained 84% of the variability of LogTS. Long-term (>35 yr) no-till combined with manuring improved the aggregate properties contrasting with conventionally cultivated systems.

THE MACROSCALE BEHAVIOR of the soil depends on the mechanical properties of individual aggregates. The structural dynamics of the whole soil is defined by the architectural organization and attributes of ever-changing aggregates as the basic units of soil structure development. Aggregates influence root growth and seedling emergence (DeFreitas et al., 1996), soil moisture retention (SMR) and airflow (Watts and Dexter, 1997), and SOC sequestration and dynamics (Denef et al., 2004). Mechanical properties of aggregates are indicative of response of the soil system to tillage, compaction, and plant growth. The properties of aggregates may differ from those of the whole soil due to the dynamics of aggregate formation (Horn, 1990; Zhang, 1994). Understanding of mechanical properties of aggregates is crucial to explain the macroscale functions of soil for plant growth (DeFreitas et al., 1996).

One of the most useful mechanical properties of aggregates is TS (Dexter and Kroesbergen, 1985; Rahimi et al., 2000). The TS refers to the force required to break an aggregate and is a very sensitive indicator of the structural stability of the whole soil (Watts and Dexter, 1998). Soils with high aggregate TS offer higher resistance to mechanical disturbance (Perfect and Kay, 1994). The TS is determined on air-dry (Munkholm and Schjonning, 2004) and oven-dry (Watts and Dexter, 1998) aggregates or in moist aggregates drained at various suction heads (Munkholm and Kay, 2002). The TS is a dynamic measure of the inter- and intra-aggregate bonds and the amount of soil aggregation (Horn and Dexter, 1989).

Importance of TS is often overlooked during soil characterization and management (Guérif, 1990). The few studies on TS show that TS is highly sensitive to soil and management (Adam and Erbach, 1992; Watts and Dexter, 1998). Intensive cultivation increases TS relative to uncultivated systems (Munkholm and Schjonning, 2004). Tillage at moisture contents above the plastic limit increases the aggregate strength compared with aggregates formed by tillage at lower moisture contents. Most of the studies on TS have been conducted on moldboard plowed and grass pasture systems (Watts and Dexter, 1998; Materechera and Mkhabela, 2001; Munkholm and Kay, 2002). Thus, data on TS from long-term no-till and other conservation practices are not well documented. Impact of long-term no-till systems on TS and related aggregate properties can differ from that of traditional practices because reduced disturbance, improved earthworm activity (Butt et al., 1999), and manuring in no-till systems can impact TS differently compared with moldboard plow systems. Furthermore, TS response to tillage can be soil specific. Benjamin and Cruse (1987) reported that soil aggregates of a Canisteo clay loam under paraplow management had lower strength than those under no-till in a Canisteo clay loam. In a Haig silt loam, however, these differences were not significant. Knowledge of differences in mechanical properties among long-term no-till and traditional tillage systems is essential to design proper management practices as stated by Munkholm and Schjonning (2004).

Aggregates tend to have higher mechanical strength than the bulk soil (Semmel et al., 1990) because they com-

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Abbreviations: CP, chisel plow; DM, disk with manure; LogTS, log-transformed tensile strength; MP, moldboard plow; NT, no-till without manure; NTM, no-till with manure; PTFs, pedotransfer functions; ρ_b, soil bulk density; ρ_{agg}, aggregate bulk density; SMR, soil moisture retention; SOC, soil organic carbon; TS, tensile strength.

monly possess higher internal friction and cohesion forces than bulk soil (Horn, 1990). Munkholm and Kay (2002) reported that TS of soil cores was significantly lower than that of individual aggregates at similar moisture content (−1000 kPa). Differences between bulk density of aggregates (ρ_{agg}) and density of bulk soil (ρ_b) can also differ. Munkholm and Kay (2002) and Schafer-Landefeld et al. (2004) observed that the ρ_{agg} from moldboard plowed soils was about 25% higher than that of ρ_b in diverse soils. Studies on management effects on ρ_b are many (Eynard et al., 2004), but few have compared ρ_b with ρ_{agg} within long-term no-till and moldboard, chisel, and disk plow systems.

Interrelationships among aggregate mechanical properties and management-induced changes in SOC are not well understood (Beare et al., 1994). For example, TS can be sensitive (Watts and Dexter, 1997) or insensitive (Causarano, 1993; Churchman et al., 1993) to changes in SOC concentration depending on soil and management conditions. Zhang (1994) reported that porosity increased by approximately 25% when organic matter (OM) increased by 8% while decreasing both the ρ_{agg} and TS of aggregates formed by artificial mixtures of soil at different rates of OM, but these relationships depended on the degree of OM decomposition. Slightly decomposed OM had greater effect on decreasing both ρ_{agg} and TS and increasing SMR than highly decomposed OM. The SOC concentration can be negatively correlated with ρ_{agg} (Hulugalle and Cooper, 1994) and positively with aggregate porosity (Poier and Richter, 1992) in the surface soils. The SMR at low suctions can be increased with increasing SOC concentration (Watts and Dexter, 1997), but few have assessed the SMR vs. SOC relationships in soil aggregates. The TS may be estimated from interdependent aggregates properties such as aggregate size, ρ_{agg}, and SOC concentration using pedotransfer functions (PTFs). Imhoff et al. (2002), using PTFs, showed that soil texture and SOC were the best predictors of TS in sandy, loamy, and clayey Oxisols. The PTFs have not been used widely to explain differences in TS among long-term management systems, yet they are important tools to complement the data analyses (Kay et al., 1997).

Literature shows that data on TS, ρ_{agg}, and SMR at the aggregate-scale under long-term no-till and other conservation practices are few. Development of PTFs using site-specific data to understand the interrelationships among aggregate properties and predict the TS for no-till and traditional agricultural practices is needed. Data on the aggregate properties under long-term no-till and traditional agricultural practices are specially lacking for the soils of the north Appalachian region. These data are needed to better understand the overall mechanical nature of the macroscale properties of soils in this region toward improving the soil management.

Thus, the objectives of this study were to: (i) assess the TS, density, moisture retention characteristics, and SOC of soil aggregates as influenced by long-term (>35 yr) no-till and traditional agricultural practices, (ii) compare the bulk densities of aggregates with those of bulk soil under diverse management practices, and (iii) study the interrelationships among aggregates properties using PTFs. Three hypotheses tested were: (i) long-term no-till and traditional agricultural practices induce significant changes in aggregate properties, (ii) soil aggregates have higher bulk density than bulk soil, and (iii) density, size, and SOC of aggregates can be potential parameters for estimating the aggregate tensile strength in long-term management systems using PTFs.

MATERIALS AND METHODS

Study Site and Management Descriptions

This study was conducted at the USDA North Appalachian Experimental Watershed (NAEW) in Coshocton County, OH. Seven watersheds under long-term (>15 yr) management practices were selected for the study as follows: moldboard plow (MP), chisel plow (CP), disk with beef cattle manure (DM), no-till with beef cattle manure (NTM), no-till without beef cattle manure (NT), pasture, and forest (Table 1). The five cultivated watersheds are small (<1 ha), while the two watersheds under forest and pasture are relatively large (>1 ha). All watersheds have undulating slopes (ranging from 6 to 23%) except for the one under the MP treatment (0.2% slope; Table 2), which is also the smallest watershed (0.12 ha) sited on the summit position. The MP, NTM, and NT are managed under continuous corn (*Zea mays* L.). The CP treatment is cropped to corn–soybean (*Glycine max* L.)/rye (*Secale cereale* L.) rotations where rye is used as a winter cover crop, while the DM is cropped to corn–soybean, and wheat (*Triticum aestivum* L.)/red clover (*Trifolium pretense* L.) rotation. Tillage operations are performed on the contour in all watersheds. The pasture is under orchardgrass (*Dactylis glomerata* L.), and forest is under white oak (*Quercus alba* L.) and red oak (*Quercus rubra* L.). Soil series and taxonomic classification differ among the watersheds but all have silt loam surface texture (Table 2). The Rayne series is the dominant soil and has better drainage than other series because of lower clay content in the B horizons (Kelley et al., 1975).

Soil Sampling and Preparation of Soil Aggregates

Bulk soil samples (1000 g) were collected from the seven watersheds in early April 2004 before seedbed preparation

Table 1. Management history of the seven watershed treatments under moldboard plow (MP), chisel plow (CP), disk with cattle manure (DM), no-till without cattle manure (NT), no-till with cattle manure (NTM), pasture, and forest at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio.

Watersheds	Management history
MP	21-yr continuous corn (*Zea mays* L.), moldboard plowed to 0.25-m depth, disked twice, and harrowed before planting; 150 kg N ha^{-1} applied as NH_4NO_3.
Chisel	15-yr corn–soybean (*Glycine max* L.)/rye (*Secale cereal* L.) rotation, chisel plowed to 0.25 m at 0.30 m spacing in spring, and 150 kg N ha^{-1} applied as NH_4NO_3 in corn year.
DiskM	15-yr wheat (*Triticum aestivum*)/red clover (*Trifolium pretense* L.)–corn–soybean rotations, shallow disking before planting. 14 Mg ha^{-1} of beef cattle manure each spring and 90 kg N ha^{-1} applied as NH_4NO_3 every 3 yr during corn rotation. The last manure application was in 2003, one year before this study.
NTM	41-yr continuous corn, manured with beef cattle manure each spring at 15 Mg ha^{-1}, 150 kg N ha^{-1} applied as NH_4NO_3, and herbicides applied for controlling weeds.
NT	35-yr continuous corn, 150 kg N ha^{-1} applied as NH_4NO_3, and herbicides applied for controlling weeds.
Pasture	Perennial orchardgrass.
Forest	Perennial hardwood forest (white and red oak).

Table 2. Soil classification of the seven watershed treatments at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio.

Watersheds	Soil Series	Soil classification	Slope
			%
MP	Rayne silt loam	Fine loamy, mixed, mesic Typic Hapludults	0.2
NTM	Rayne silt loam	Fine loamy, mixed, mesic Typic Hapludults	6–12
NT	Rayne silt loam	Fine loamy, mixed, mesic Typic Hapludults	6–12
CP	Keene silt loam	Fine-silty, mixed, mesic Aquic Hapludalfs	7
DM	Coshocton-Rayne silt loams	Fine loamy, mixed, mesic Aquic Hapludalfs; Typic Hapludults	12–18
Pasture	Rayne silt loam	Fine loamy, mixed, mesic Typic Hapludults	12–18
Forest	Coshocton-Rayne silt loams	Fine loamy, mixed, mesic Aquic Hapludalfs	18–23

and almost one year after tillage, which is performed on late April or early May. Soil samples in triplicate were taken from the summit position of each watershed at 0- to 10-, 10- to 20-, and 20- to 30-cm depths. Soil samples with depth were collected from three sampling positions 3-m apart along the contour within the summit position. A total of 63 (7 treatments × 3 depths × 3 reps) soil samples were collected, transported to the laboratory, air-dried at about 22°C for 72 h (Nelson and Sommers, 1996), and then gently crushed (Dexter and Watts, 2001). The air-dried and crushed samples were dry-sieved through a nest of sieves with 1-, 2-, 4-, 6-, and 8-mm openings to obtain four aggregate-size classes (1–2, 2–4, 4–6, and 6–8 mm). Use of air-dry aggregates for evaluating soil management impacts on SOC and mechanical properties of aggregates is a common approach (Nelson and Sommers, 1996; Dexter and Watts, 2001; Munkholm and Schjonning, 2004). Air-drying of aggregates is not expected to significantly influence the relative differences among the treatments because soil texture for the seven treatments was similar (Shukla et al., 2003).

Determination of Tensile Strength

The TS of the aggregates was determined using the crushing method (Dexter and Kroesbergen, 1985; Dexter and Watts, 2001). The TS of air-dry aggregates was measured at a suction of about −160 MPa based on a constant room temperature of 22°C and 33% of relative humidity. A total of 756 aggregates (7 treatments × 3 reps × 3 subsamples per rep × 3 depths × 4 aggregate-size fractions) were used for the TS test. An additional three subsamples of aggregates per replicate were used during the test to account for the high variability of TS values. A simple apparatus based on a design by Horn and Dexter (1989) was constructed and used for the crushing test. The test consisted of placing an individual aggregate between the two round plates of the apparatus and recording the force (F) needed to crush the aggregate. The TS of aggregates was computed using Eq. [1] (Rogowski et al., 1968):

$$\mathrm{TS} = 0.576\left(\frac{F}{d_{\mathrm{agg}}^2}\right) \qquad [1]$$

where F is the breaking force (N), d_{agg} is the mean aggregate diameter (m) assuming that the aggregate is homogeneous, isotropic, and has a uniform deformation during the test. The d_{agg} was computed using the approach "Method 1 and 2" by Dexter and Kroesbergen (1985). The diameter of upper (s_1) and lower (s_2) sieve sizes was averaged to compute the d_{agg} for the 1- to 2- and 2- to 4-mm aggregates using Eq. [2] ("Method 1").

$$\text{Method1: } d_{\mathrm{agg}} = \frac{s_1 + s_2}{2} \qquad [2]$$

The d_{agg} of the 4- to 6- and 6- to 8-mm aggregates was measured with a caliper ("Method 2") in addition to using "Method 1" for comparison purposes. The longest (d_1), intermediate (d_2), smallest (d_3) diameter of each aggregate was recorded to estimate the d_{agg} using Eq. [3]. Mean d_{agg} between "Method 1 and 2" for the 4- to 6- and 6- to 8-mm sized aggregates was not significant.

$$\text{Method2: } d_{\mathrm{agg}} = \frac{d_1 + d_2 + d_3}{3} \qquad [3]$$

Aggregate Density

The density of the individual aggregates was measured using the clod method (Brasher et al., 1966; Grossman and Reinsch, 2002). Oven-dry aggregates from each fraction (1–2, 2–4, 4–6, and 6–8 mm) were weighed and then coated with Saran resin. Each coated aggregate was weighed before immersing it in distilled water at 20°C. After immersion, the aggregate was weighed again to determine its weight loss. The weight loss equals the volume of the coated aggregate. Because Saran resin coating increases the total weight and volume of the aggregate, the ρ_{agg} was adjusted for the weight and volume of Saran. Weight of aggregates before and after coating with Saran resin was used to determine the weight of Saran. The ρ_{agg} was computed with Eq. [4]

$$\rho_{\mathrm{agg}} = \frac{\rho_{\mathrm{w}} W_{\mathrm{d}}}{\left[W_{\mathrm{spw}} - \left(\dfrac{\rho_{\mathrm{w}} W_{\mathrm{pa}} f}{\rho_{\mathrm{s}}}\right)\right]} \qquad [4]$$

where W_{d} is the weight of oven-dry aggregate (g), W_{spw} is the aggregate weight after immersion (g), W_{pa} is the weight of Saran resin (g), f is the factor for Saran resin absorbed into the aggregate, ρ_{w} is the density of water at 20°C (g cm^{-3}), and ρ_{s} is the density of Saran resin coating (approximately 1.3 g cm^{-3}; Grossman and Reinsch, 2002). The values of f were 1.0 for the 1- to 2- and 2- to 4-mm, 0.6 for the 4- to 6-mm, and 0.3 for the 6- to 8-mm aggregates (Munkholm and Kay, 2002). The ρ_{agg} was determined on 252 aggregates (7 treatments × 3 reps × 3 depths × 4 aggregate size fractions). Sixty-three soil cores (5.3 cm high by 6.0 cm diam.) were collected from the same seven watersheds treatments and depths to compare differences between ρ_{agg} and ρ_{b}. Samples for the determination of ρ_{agg} and ρ_{b} were collected at the same time. The ρ_{b} was measured using the core method (Grossman and Reinsch, 2002).

Soil Moisture Retention and Soil Organic Carbon

The SMR of aggregates was determined at 0, −1.5, −3, −6, −10, −33, −100, and −333 kPa for 2- to 4- and 6- to 8-mm aggregates from two soil depths (0–10 and 10–20 cm). Forty-two air-dry aggregates (7 treatments × 2 depths × 3 reps) were used at each suction level. The SMR at 0 through −10 kPa was determined using a tension table equipped with a capillary outflow tube (Dane and Hopmans, 2002). The aggregates were weighed and capillary wetted to saturation on the tension table, and then they were sequentially drained to −1.5, −3.0, −6.0, and −10 kPa by lowering the tip of the outflow tube to the desired pressure head and determining the moisture content of the aggregate after drainage has ceased at each pressure head. Aggregates in triplicate per treatment, depth, and aggregate size were randomly withdrawn at each suction level for the moisture content determination using the gravimetric approach (Topp and Ferré, 2002). The SMR at high suction levels (−33, −100, −333 kPa) was determined with a pressure plate apparatus (Dane and Hopmans, 2002). Aggregates were carefully transferred from the tension table to the pressure plate apparatus and then drained at each suction level. Each aggregate-size fraction (1–2, 2–4, 4–6, and 6–8 mm) was ground separately and sieved through 0.25 mm for the total SOC concentration determination by dry combustion method (900°C) using a CN analyzer (Vario Max, Elementar Americas, Inc., Germany) (Nelson and Sommers, 1996).

Statistical Analyses

The analysis was treated as a randomized experiment. A split-plot design was used to determine whether differences in TS, ρ_{agg}, and SOC concentration among the seven management practices were the same by depth. The main factor for the split-plot design model was the management practice, while the subplot-factor was the aggregate size. Correlation matrix and simple regression fits among aggregate-size fractions, TS, ρ_{agg}, SMR, and SOC concentration were computed, and relationships among these properties were studied before the development of PTFs using multivariable regression analysis. Differences between ρ_{agg} and ρ_b were compared using the Student's *t* test distribution. Statistics were performed using the SAS statistical software (SAS Institute, 1999). Normality of the data was tested with the Shapiro–Wilk's W-test using the UNIVARIATE procedure in SAS (Shapiro and Wilk, 1965).

RESULTS AND DISCUSSION

Tensile Strength

Statistical analyses on TS of soil aggregates were conducted in log-transformed data to stabilize the variance. Geometric means of TS with depth by treatment are plotted in Fig. 1. The interaction treatment × aggregate size was not significant. Management practices had a significant effect on the TS ($P < 0.01$). The TS decreased in the order: MP = CP > DM = Pasture > NTM = NT > Forest in the 0- to 10-cm depth. Aggregates under forest had the lowest TS (63 kPa) for the three depths ($P < 0.01$; Fig. 1). Results are in accord with other studies, which indicate that forest soils often have weaker aggregates than arable soils because of improved soil structure and high SOC concentration (Watts and Dexter, 1998). The NTM and NT had lower TS than MP, CP, DM, and pasture treatments for the 0- to 20-cm soil depth ($P < 0.01$; Fig. 1), indicating that aggregates under the no-till treatments were weaker than those under other treatments except under the forest. The TS for NTM and NT was lower by a factor of 2.5 than that for MP and CP, and 2 than that for DM and pasture for 0- to 10-cm depth. The lower TS for NTM and NT could be ascribed to high SOC concentration and possibly to earthworm activity. Butt et al. (1999) observed that NTM and NT had more earthworms (*Lumbricus terrestris* L.) and earthworm casts than MP soils in the same

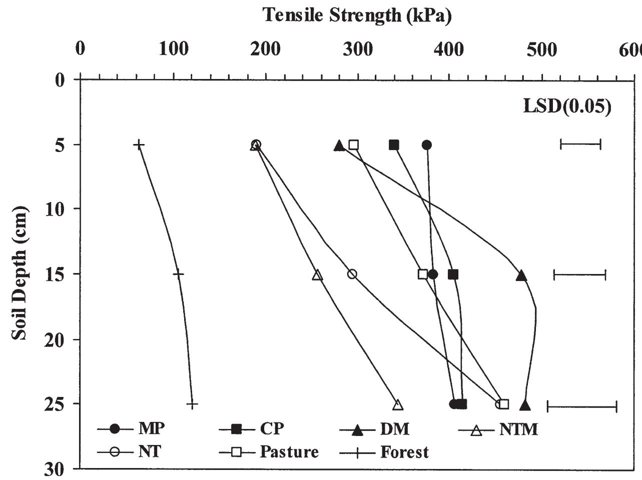

Fig. 1. Differences in geometric mean tensile strength of aggregates among moldboard plow (MP), chisel plow (CP), disk with cattle manure (DM), no-till without cattle manure (NT), no-till with cattle manure (NTM), pasture, and forest treatments.

watersheds. Ley et al. (1989) also reported that TS of aggregates in no-till was lower by a factor of 1.4 than that in MP in a loamy soil.

Results show that the MP produced the highest TS (377 kPa) followed by the CP treatment (340 kPa) for 0- to10-cm depth, but not at lower depths. The higher TS in MP implies that post-tillage consolidation of excessively tilled soils can result in denser, more compact, and stronger aggregates compared with no-till, pasture and forest management (Causarano, 1993; Munkholm and Kay, 2002). Results show that TS decreased with decreasing tillage intensity. The high TS of tilled soils may increase the tillage work and impede a normal penetration and growth of roots (Guérif, 1990). We conjecture that the TS of aggregates may be a more sensitive parameter governing the root growth than the bulk soil strength especially when roots penetrate aggregates.

There was a sharp increase in TS with soil depth in all but the MP treatment (Fig. 1). The uniform mechanical disturbance of the plow layer in MP soils may explain the small change of TS with depth. The increase of TS with depth is possibly due to increase in clay content, soil consolidation, and low SOC concentration and biological activity. The TS in DM for the 10- to 20-cm depth was 70% higher than that for the 0- to 10-cm depth. This rapid increase in TS may be attributed to the plowpan formation in the subsoil. The increase of TS with depth for the NTM was not as pronounced as that for the NT treatment, indicating that manuring in association with bioturbation by earthworm activity most likely reduced the TS in the NTM treatment. Manuring modifies the soil matrix by buffering the excessive consolidation of soil dry aggregates and by improving the overall structural strength of the soil (Guérif, 1990).

Aggregate Density

Mean ρ_{agg} by treatment and aggregate size is shown in Tables 3 and 4. The interaction treatment × aggregate size was not significant for the 0- to 10- and 10- to 20-cm depth, but it was significant for the 20- to 30-cm depth.

Table 3. Mean values ($n = 3$) of aggregate density for moldboard plow (MP), chisel plow (CP), disk with cattle manure (DM), no-till without cattle manure (NT), no-till with cattle manure (NTM), pasture, and forest treatments by aggregate size and soil depth.

Treatment	Aggregate size, mm 1–2	2–4	4–6	6–8	Pooled STD†
	Mg m^{-3}				
	0–10 cm				
MP	1.59	1.58	1.59	1.58	0.04
CP	1.71	1.65	1.62	1.61	0.05
DM	1.47	1.46	1.45	1.43	0.01
NT	1.49	1.48	1.48	1.47	0.01
NTM	1.21	1.13	1.06	1.05	0.08
Pasture	1.35	1.27	1.25	1.24	0.05
Forest	1.06	1.04	1.01	0.83	0.10
	10–20 cm				
MP	1.42	1.42	1.50	1.48	0.04
CP	1.51	1.50	1.52	1.51	0.01
DM	1.40	1.39	1.46	1.44	0.03
NT	1.44	1.45	1.47	1.46	0.01
NTM	1.27	1.27	1.22	1.25	0.05
Pasture	1.38	1.39	1.41	1.43	0.02
Forest	1.15	1.11	1.08	1.10	0.03
	20–30 cm				
MP	1.26	1.48	1.56	1.61	0.15
CP	1.77	1.66	1.63	1.56	0.09
DM	1.23	1.37	1.39	1.45	0.09
NT	1.43	1.54	1.50	1.51	0.05
NTM	1.51	1.51	1.63	1.59	0.06
Pasture	1.53	1.41	1.41	1.47	0.06
Forest	1.19	1.28	1.28	1.27	0.05

† Pooled STD is the pooled standard deviation of the means across aggregate sizes.

Management had a large effect on ρ_{agg} ($P < 0.01$; Table 4). Mean ρ_{agg} decreased in the order: CP > MP > DM = NT > Pasture > NTM > Forest for the 0- to 10-cm, and CP = MP > DM = NT = Pasture > NTM > Forest for the 10- to 20-cm depth. The lowest ρ_{agg} (0.99 Mg m^{-3}) was observed for forest. The ρ_{agg} for NTM was lower by a factor of 1.4 than that in MP and CP and higher by a factor of 1.1 than that in forest. The ρ_{agg} for NTM was 30% lower than that for NT ($P < 0.01$) in the 0 to 10 cm, which is probably attributed to the marked effect of manuring on reducing ρ_{agg}. As with TS, differences in ρ_{agg} between no-till treatments and forest were smaller than those between MP and forest, which strongly suggests that tilled soils had greater effect on increasing the ρ_{agg} compared with NTM and NT. The high ρ_{agg} in tilled soils may be due to decreased macroporosity and increased post-tillage consolidation of soil aggregates in concomitance with the low SOC concentration. Similarly, Watts and Dexter (1997) reported that ρ_{agg} in tilled soils was 30% higher than that in pasture in a silt loam soil. The low ρ_{agg} for forest and pasture is likely related to increased SOC concentration and bioturbation, which dilute the ρ_{agg} near the surface (Munkholm and Kay, 2002).

Aggregate Density vs. Density of Bulk Soil

Differences between ρ_{agg} and ρ_b were compared using ρ_{agg} data for the 1- to 2- and 6- to 8-mm aggregates and ρ_b data, and the differences depended on the soil depth. The ρ_{agg} was significantly higher than ρ_b for all treatments for the 0- to 10-cm depth ($P < 0.05$). Differences below 10-cm depth were small and not significantly different at the 0.05 level. Comparison of mean values of ρ_{agg} with ρ_b by treatment for the 0- to 10-cm depth is presented in Fig. 2. The absolute difference between ρ_{agg} for the 1- to 2-mm aggregates and ρ_b for the CP, NT, and forest soils was markedly higher than that for other treatments. The absolute difference between ρ_{agg} and ρ_b decreased as aggregate size increased. The ρ_{agg} of the 6- to 8-mm aggregates was significantly higher than ρ_b only for the NT treatment (Fig. 2). This trend suggests that differences between ρ_{agg} and ρ_b decreased with increasing size of aggregates, attributable to the fact that increasingly large aggregates probably resemble the character of bulk soil better than small aggregates. The higher ρ_{agg} of 1- to 2-mm aggregates may be due to the (i) reduction of macroporosity and earthworm activity, and (ii) increase of cohesion forces, contact points, and bonding energy mechanisms within aggregates as compared with the bulk soil (Horn, 1990).

Table 4. Aggregate density (ρ_{agg}) averaged ($n = 21$) across treatments and aggregate-size fractions for the 0- to 10- and 10- to 20-cm soil depths. Average ρ_{agg} over treatments and aggregate-size classes for the 20 to 30 cm are not included because of significant interaction.

Factors	ρ_{agg} 0–10 cm	10–20 cm
Treatment	Mg m^{-3}	
MP	1.55	1.46
CP	1.65	1.51
DiskM	1.45	1.42
NT	1.48	1.45
NTM	1.11	1.26
Pasture	1.27	1.40
Forest	0.99	1.11
LSD(0.05)	0.07	0.05
Aggregate size, mm		
1–2	1.4	1.38
2–4	1.36	1.36
4–6	1.35	1.38
6–8	1.31	1.37
LSD(0.05)	0.06	0.03

Soil Moisture Retention

The SMR curves for each management are shown in Fig. 3. Management changed significantly the SMR regimes in both 2- to 4- and 6- to 8-mm aggregates ($P < 0.01$). Soil aggregates under NTM retained the highest amount of moisture, whereas those under MP treatment retained the lowest (0 to −333 kPa). Differences in SMR between NTM and MP were larger between 0 and −33 kPa than between −33 and −333 kPa (Fig. 3). Large differences at low tensions are most likely due to increased macroporosity in NTM soils. The 6- to 8-mm aggregates under forest retained significantly less moisture than NTM. However, forest had greater SMR capacity than pasture, NT, DM, CP, and MP at greater than −33 kPa, but the differences at lower than −33 kPa were mixed. The absolute difference in moisture content between NTM and forest increased at lower than −33 kPa, thereby implying that soil aggregates under forest drain more rapidly and thus retain less moisture than those under NTM. Differences in SMR

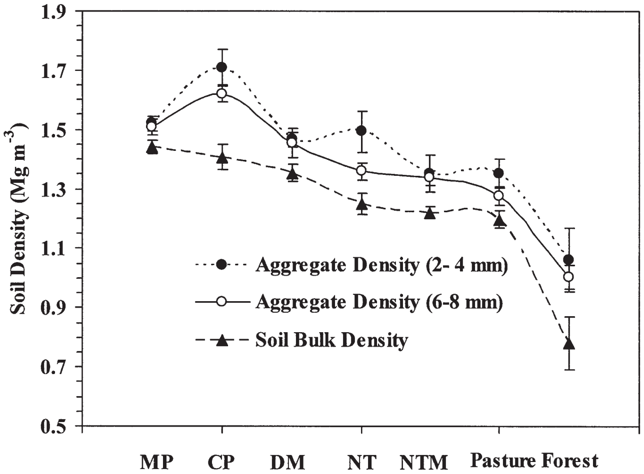

Fig. 2. Differences in densities between aggregates and bulk soil for long-term moldboard plow (MP), chisel plow (CP), disk with cattle manure (DM), no-till without cattle manure (NT), no-till with cattle manure (NTM), pasture, and forest management practices for the 0- to 10-cm depth. Error bars represent the standard deviation of the means (n = 3).

among the treatments decreased as moisture potential decreased. Aggregates from MP, CP, and DM retained consistently less moisture than the rest of the treatments, particularly at low suctions, suggesting that the combined effect of increased soil disturbance and low SOC reduced the SMR capacity in tilled treatments, and this effect was the greatest for the MP treatment. These results support those of Watts and Dexter (1997), who reported that SMR in aggregates decreased with increasing soil disturbance in a silty clay loam soil. The small differences in SMR among treatments at higher suctions are attributed to the higher proportion of soil moisture held in mesopores and micropores. The SMR at low tensions is often controlled by differences in macroporosity and macroscale soil structural characteristics, while SMR at high suctions depends primarily on adsorption and specific surface area of soil particles (Miller et al., 2002). Combination of no-till with manuring greatly improved the SMR capacity of soil aggregates as compared with moldboard-plowed soils.

Soil Total Organic Carbon

The SOC pools are shown in Table 5, and the SOC concentration in Fig. 4. No significant differences in trends between pool and concentration of SOC existed. The SOC concentration decreased in the order: Forest > NTM > Pasture > NT = DM > CP = MP (Fig. 4; $P <$ 0.01). The SOC concentration for NTM was significantly higher than that for NT, attributed to manuring. The SOC concentration in NT was significantly lower than that in forest, NTM, and pasture for all aggregate sizes. The SOC concentration for the DM was higher by a factor of 1.7 than the average for MP and CP, but it was not significantly different from that for NT. The higher SOC concentration in DM than in MP and CP is attributable to the manuring effect. Differences in SOC concentration among the aggregate-size fractions depended on the treatment (Fig. 4). The SOC concentration decreased quadratically with increasing aggregate size in forest and somewhat similarly in NTM. This finding is similar to that observed by Baldock et al. (1987) in which SOC concentration in soils under 15-yr continuous pasture and corn in a silt loam decreased as aggregate size increased from 0.1 to 8 mm. This study shows, however, that differences in SOC concentration among MP, CP, DM, NT, and pasture by aggregate size were not significant. Relationships between SOC concentration vs. aggregate size are often mixed. The SOC concentration can increase (Baldock et al., 1987), decrease (Cambardella and Elliot, 1993) or remain unchanged (Beare et al., 1994) with decreasing aggregate size.

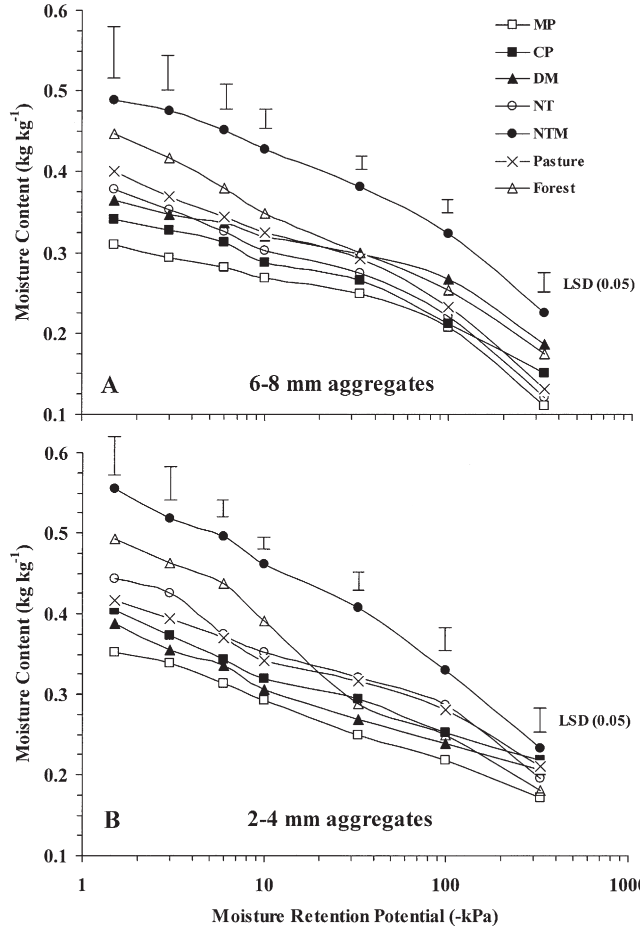

Fig. 3. Moisture retention curves for the 2- to 4- and 6- to 8-mm aggregates under moldboard plow (MP), chisel plow (CP), disk with cattle manure (DM), no-till without cattle manure (NT), no-till with cattle manure (NTM), pasture, and forest treatments for the 0- to 10-cm depth.

Interrelationship among Aggregate Properties and Development of Pedotransfer Functions Tensile Strength and Aggregate Density vs. Aggregate Size

The TS and ρ_{agg} varied with aggregate size ($P < 0.01$; Fig. 5A). The TS was negatively correlated with aggregate size and increased quadratically with decreasing aggregate size for all depths ($r^2 \approx -0.99$). There was a slow increase in TS between 4 and 8 mm and a more

Table 5. Total organic C pool for moldboard plow (MP), chisel plow (CP), disk with cattle manure (DM), no-till without cattle manure (NT), no-till with cattle manure (NTM), pasture, and forest by aggregate size and soil depth.

Aggregate size	Land use and management practices							LSD(0.05)
	MP	CP	DM	NT	NTM	Pasture	Forest	
mm	Mg ha^{-1}							
					0–10 cm			
1–2	21.7	21.0	35.3	31.7	58.5	38.9	74.1	6.5
2–4	18.9	20.5	35.2	31.9	51.8	34.7	61.1	4.6
4–6	19.6	19.8	34.9	33.6	48.6	33.8	54.9	4.3
6–8	19.0	19.7	34.4	32.0	48.7	34.1	47.1	6.0
LSD(0.05)	2.3	3.6	5.6	4.1	5.4	4.7	11.6	
					10–20 cm			
1–2	40.5	34.6	39.8	23.4	65.5	40.5	42.2	4.2
2–4	39.6	34.2	40.0	23.9	62.4	39.7	39.6	3.2
4–6	42.1	34.1	40.3	22.9	55.9	38.8	41.3	4.1
6–8	39.6	34.4	41.1	20.1	48.8	36.1	38.3	1.9
LSD(0.05)	2.0	2.4	1.8	4.6	4.4	4.1	7.0	
					20–30 cm			
1–2	34.1	46.0	30.4	31.4	49.2	45.9	39.1	6.7
2–4	38.1	40.6	32.8	35.3	47.5	41.0	41.1	2.5
4–6	44.1	41.8	30.0	33.7	47.0	40.0	41.7	2.6
6–8	38.8	39.0	32.9	33.1	46.4	42.4	39.3	7.3
LSD(0.05)	7.2	2.3	3.3	6.4	7.3	4.0	7.2	

rapid increase for <4-mm aggregates (Fig. 5A). Chan et al. (1999) also observed that TS of 3.4 mm was 1.2 times higher than that in 5.8 mm and about two times higher than that in 7.94- and 11.1-mm aggregates in a clayey soil. The low TS for large aggregates is most likely due to the fact that large aggregates possess more planes of failure, more microcracks, and weaker contact points than small aggregates, which act on reducing the resistance of aggregates to disruption (Utomo and Dexter, 1981). Small aggregates are often more stable than large aggregates because of finer intra-aggregate pores and denser packing of mineral particles (Horn and Dexter, 1989).

Relationships between ρ_{agg} and aggregate size varied with soil depth (Table 4). The ρ_{agg} increased with decreasing size of aggregates in the 0- to 10-cm depth, but there was no clear trend in the 10- to 20-cm depth. The increase of ρ_{agg} with decreasing aggregate size was more pronounced for NTM, pasture, and forest than for tilled soils (Table 3), implying that manuring and reduced soil disturbance have a greater effect on decreasing ρ_{agg} with size. The significant treatment × aggregate size interaction for the 20- to 30-cm depth is illustrated by the fact

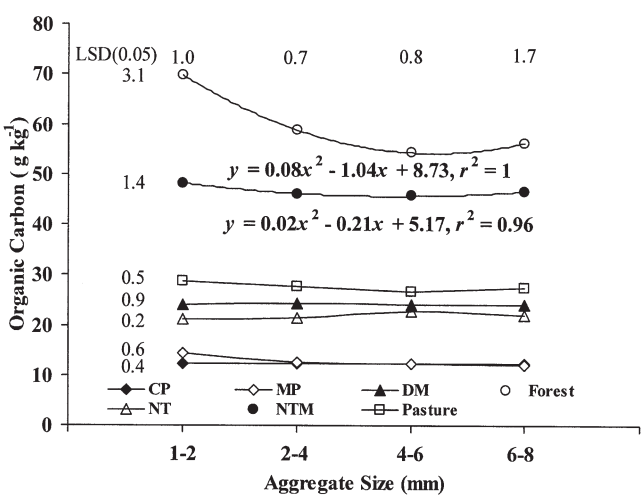

Fig. 4. Differences in soil organic carbon for moldboard plow (MP), chisel plow (CP), disk with cattle manure (DM), no-till without cattle manure (NT), no-till with cattle manure (NTM), pasture, and forest treatments by aggregate size for the 0- to 10-cm depth.

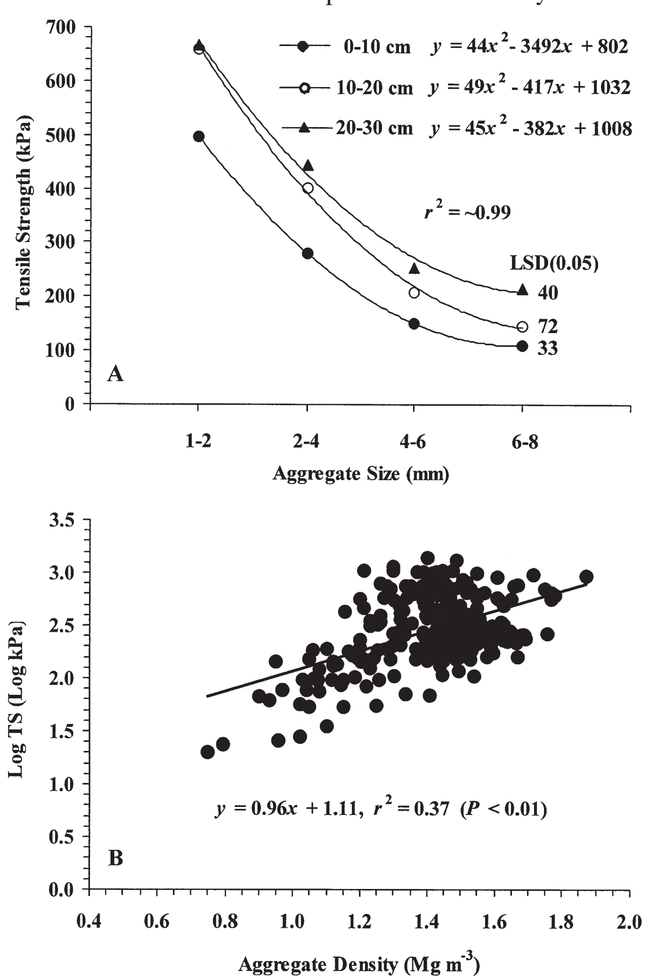

Fig. 5. Geometric mean tensile strength as a function of aggregate size (A) and log-transformed tensile strength (LogTS) as a function of bulk density of aggregates (B; n = 252).

Table 6. Correlation among aggregate properties across all treatments, aggregates sizes and soil depths. The values in parentheses are the probability levels.

	LogTS	ρ_{agg}	SOC	Aggregate size
LogTS	1.00			
ρ_{agg}	0.61 (<0.01)	1.00		
SOC	−0.44 (<0.01)	−0.66 (<0.01)	1.00	
Aggregate size	−0.67 (<0.01)	0.01 (0.98)	−0.04 (0.50)	1.00

† LogTS, log-transformed tensile strength; ρ_{agg}, aggregate bulk density; SOC, soil organic C.

that the ρ_{agg} for the MP, DM, NT, NTM, and forest increased, whereas the ρ_{agg} for CP and pasture decreased with increasing aggregate size (Table 3). Mean ρ_{agg} for the 6- to 8-mm was 8% lower than that for 1- to 2-mm aggregates for the 0 to 10 cm ($P < 0.05$). Results for the surface soil support those of Larson and Padilla (1990), which observed that ρ_{agg} of <0.5 mm was 1.7 times higher than that in 5- to 10-mm aggregates in silty clay and loamy soils. Large aggregates often exhibit more macropores than small aggregates, thereby lowering the ρ_{agg}.

Tensile Strength and Soil Moisture Retention vs. Aggregate Density

The LogTS of aggregates increased as the ρ_{agg} values increased ($P < 0.01$; Fig. 5B). The relationship between ρ_{agg} and LogTS data points for all treatments, depths, and aggregate sizes was described by a linear equation, in which the ρ_{agg} explained 37% of the variance of LogTS of aggregates (Fig. 5B). The SMR was negatively correlated with ρ_{agg} ($r = -0.28$) between 0 and −6 kPa, and this correlation was significant at the 0.10 probability level. These results show that SMR of aggregates increased with a decrease in ρ_{agg}. The higher SMR of aggregates from NTM and forest soils probably resulted from the lower aggregate densities. Studies relating SMR to TS and ρ_{agg} in discrete aggregates are few. Watts and Dexter (1997) reported that SMR at low tensions increased markedly as ρ_{agg} decreased among management practices in silt loam soils.

Aggregate Properties vs. Soil Organic Carbon

The LogTS, ρ_{agg}, and SMR of aggregates were influenced significantly by the SOC concentration (Tables 6 and 7). The LogTS was negatively and strongly correlated ($r = -0.67$) with SOC concentration ($P < 0.01$). Increase in SOC concentration reduced the strength of air-dry aggregates. The SOC concentration explained 36% of the variability in LogTS (Fig. 6A). Zhang (1994) also observed that TS decreased with the addition of slightly humidified peat moss as OM source in a silt loam and clay soils. However, our results contrast with those reported by Ekwue (1990), in which the TS under grass treatment increased ($r = 0.72$) with increasing SOC concentration in a sandy loam and sandy clay loam soils. Others report that TS is relatively insensitive to changes in SOC concentration (Watts and Dexter, 1997). These contradictory findings suggest that the influence of SOC on aggregate strength can be variable and may depend on the interactions of SOC with soil texture (Imhoff et al., 2002), degree of OM humification (Ekwue, 1990), physical and chemical status of the OM (Zhang, 1994), and management.

The SOC concentration was also highly correlated with ρ_{agg} (Tables 6 and 7), and it explained about 80% of the variability in ρ_{agg} (Fig. 6B). The negative correlation indicates that the increase in SOC reduced the ρ_{agg}. Watts and Dexter (1997) also observed significant reduction in ρ_{agg} with increasing SOC among pasture and tillage treatments. The reduction of ρ_{agg} had additive effects on reducing TS and increasing SMR. The lower ρ_{agg} and

Table 7. Correlation among selected properties for the 2- to 4- and 6- to 8-mm aggregates for the 0- to 10-cm depth. The values in parentheses are the probability levels.

Properties†	ρ_{agg}	SOC
SOC	−0.90 (<0.01)	
	Moisture potential	
−1.5 kPa	−0.27 (0.08)	0.40 (<0.01)
−3.0 kPa	−0.30 (0.05)	0.40 (<0.01)
−6.0 kPa	−0.23 (0.14)	0.35 (<0.02)
−10 kPa	−0.17 (0.27)	0.29 (0.06)
−33 kPa	−0.01 (0.94)	0.04 (0.78)
−100 kPa	−0.08 (0.63)	0.35 (0.52)
−333 kPa	0.18 (0.26)	−0.08 (0.60)

† SOC, soil organic C; ρ_{agg}, aggregate bulk density.

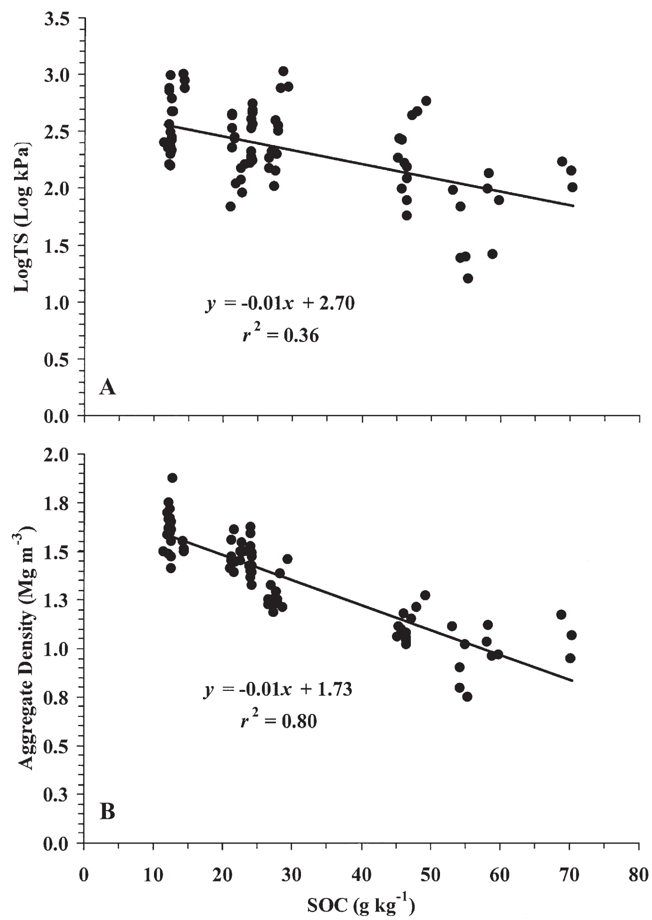

Fig. 6. Response of (A) log-transformed tensile strength (LogTS) and (B) aggregate density to changes in soil organic carbon (SOC) in the 0- to 10-cm soil depth.

higher SOC concentration most likely explain the higher SMR in forest and NTM, and pasture. The SMR of aggregates increased with increasing SOC concentration at low tensions ($P < 0.05$; Table 7). The SOC has a high specific surface area and thus it adsorbs more moisture than inorganic particles, improving the overall SMR capacity of the aggregates (Miller et al., 2002). The weak correlation at higher tensions disagrees with some of the previous studies. Zhang (1994) observed a strong correlation between SOC and SMR at all potentials from 0 to −1000 kPa. However, the low relationship at higher potentials is not uncommon. Changes in SMR with increasing potentials can be more sensitive to soil texture and TS than to SOC concentration only (Kay et al., 1997; Rawls et al., 2003).

Development of Pedotransfer Functions for the Tensile Strength

The PTFs developed based on the correlations among aggregate properties showed that LogTS can be predicted satisfactorily using aggregate size, ρ_{agg}, and SOC concentration (Table 8). The PTFs were highly significant and explained about 84% of the variability between LogTS and the independent input parameters. The PTFs showed that LogTS decreased with increasing size of aggregates, decreasing ρ_{agg}, and increasing SOC concentration of aggregates. Aggregate size was an essential input parameter for the prediction of LogTS and was present in all the PTFs. The SOC concentration and ρ_{agg} were not significant predictors of LogTS for the MP treatment, probably due to soil mixing in the plow layer that reduced differences in SOC concentration and ρ_{agg} with depth. The ρ_{agg} was also an important input parameter as the correlation between ρ_{agg} and LogTS was high. Imhoff et al. (2002) showed that SOC concentration in interaction with soil texture was the most dominant determinant affecting the TS of aggregates in soils with high concentrations of aggregate stabilizing oxides (Oxisols). Few studies have utilized PTFs based on ρ_{agg}, aggregate size, and SOC as input for predicting the TS of aggregates, yet this study shows that PTFs can be a potential approach to understand and estimate the interrelationships among aggregate properties in long-term no-till and traditional agricultural practices. Results show that TS is the result of a cumulative effect of SOC concentration, size, and bulk density of aggregates in response to soil management.

Table 8. Pedotransfer functions for predicting the log-transformed TS (LogTS) of aggregates (n = 252). All the functions were significant at the 0.01 probability level.

Treatments†	Pedotransfer functions for LogTS	r^2
MP	3.16 − 011size	0.86
CP	$3.82 - 0.10\text{size} + 0.32\rho_{agg} - 0.21\text{SOC}$	0.81
DM	$3.33 - 0.10\text{size} + 0.54\rho_{agg} - 0.15\text{SOC}$	0.88
NT	$3.24 - 0.10\text{size} + 0.54\rho_{agg} - 0.20\text{SOC}$	0.85
NTM	$2.19 - 0.10\text{size} + 0.53\rho_{agg}$	0.85
Pasture	$3.26 - 0.11\text{size} - 0.09\text{SOC}$	0.83
Forest	$1.79 - 0.10\text{size} + 0.68\rho_{agg} - 0.03\text{SOC}$	0.80
All treatments	$2.35 - 0.10\text{size} + 0.54\rho_{agg} - 0.71\text{SOC}$	0.71

† MP, moldboard plow; CP, chisel plow; DM, disk with manure; NT, no-till; NTM, no-till with manure.

CONCLUSIONS

This study shows that:

1. Long-term no-till and traditional agricultural practices impact significantly on the aggregate properties of the soils in the North Appalachian region. The NTM system has the lowest TS and the highest SOC in the 0- to 10-cm soil depth when compared with MP and CP except forest. Thus, manuring is a potential means to reduce TS, increase SOC concentration, and improve the SMR of aggregates. Excessive tillage, rapid post-tillage consolidation, and low SOC concentration are the probable reasons for the higher TS and ρ_{agg} in tilled treatments.
2. The ρ_{agg} is significantly higher than ρ_b for all management treatments. The differences between ρ_{agg} and ρ_b decrease as aggregate size increases. This trend may be due to the fact that larger aggregates resemble better the nature of bulk soil than small aggregates. Reduction of macroporosity and earthworm activity and increase of cohesion forces and contact points within aggregates may explain their high ρ_{agg}.
3. Increase in SOC concentration reduces ρ_{agg} and TS while increasing SMR between 0 and-10 kPa. The LogTS increases with increasing ρ_{agg}. Interrelationships among properties are management-dependent. Aggregate size, ρ_{agg}, and SOC concentration account for approximately 84% of the variability of LogTS using PTFs, but the predictive capacity of each aggregate property varies with management. Results show that PTFs offer potential to predict the aggregate strength from related properties in long-term management practices.

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